SALTWATER INTRUSION AND ARTIFICIAL RECHARGE MODELLING IN THE COASTAL AQUIFER SYSTEM OF CAPOTERRA (SOUTHERN SARDINIA)

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ABSTRACT

The hydrogeological, conceptual, and mathematical models have been defined to study saltwater intrusion phenomena in the coastal aquifer system of the alluvial plain of Capoterra (southern Sardinia, Italy). Pumping tests and artificial recharge experiments are carried out in the plain so as to verify the efficiency of a hydrodynamic barrier aimed at controlling saltwater encroachment and its spatial evolution.

INTRODUCTION

The alluvial plain of Capoterra is located in the south-western portion of the Campidano plain, to the west of Cagliari. The hydrogeological model of the study area is highly complex due not only to natural factors, such as local geology, the nearby sea, the presence of saltworks and a lagoon, but also to human activities, such as increasing industrial expansion and agriculture. The coastal aquifer system of the plain is subject to saltwater intrusion, exacerbated by long periods of drought, and by uncontrolled well pumping for drinking water, industry and agriculture.

The Engineering Geology and Applied Geophysics Section of the Territorial Engineering Department of the University of Cagliari is carrying out comprehensive field activity in the investigation area by means of hydrogeological and hydrogeochemical measurements taken at selected observation wells from among the many wells present in the plain, and pumping tests and artificial recharge experiments at wells and purpose built piezometers. The main objectives of this activity are to determine the hydrogeological and physical-chemical parameters of the aquifers, to validate the saltwater intrusion mathematical model, and to verify both the artificial recharge effects on groundwater quality and the efficiency of the hydrodynamic barrier in controlling saltwater encroachment.

DESCRIPTION OF THE STUDY AREA

The alluvial plain of Capoterra, situated in the south-western portion of the Campidano graben, is bounded on the western edge by granite hills, on the northern edge by the Cixerri river, and on the south-eastern edge by the S.Gilla lagoon, the saltworks, and the Mediterranean Sea. The geological formations are, from top to bottom, aquifer detritus, fluvial and lacustrine sediments, recent and ancient terraced alluvia of the Quaternary, and fractured granites and metamorphic schists of the Paleozoic. The recent alluvial deposits are very permeable and contain a phreatic aquifer, overlaying another multilayer aquifer, semi or locally confined.

The hydrogeological and hydrogeochemical study, based upon data from the control and monitoring network present in the plain, has demonstrated that (Barrocu *et al.*, 1993):

i. both phreatic and confined aquifers are laterally recharged from the west through the major fractures of the granite bedrock, and do not receive any water from the Cixerri river basin. In the aquifers there are depressions of piezometric surfaces to below mean sea level where over-exploitation occurs, due to high density of agricultural and industrial activities (Figure 1);
ii. the reference freshwater of the aquifers is chemically similar and related to the groundwater of the granitic bedrock on the west of the plain;
iii. in the confined aquifer salinity is due to seawater encroachment in the area where groundwater is highly developed to meet agricultural and industrial demands (Figure 2b);
iv. in the phreatic aquifer salinity is also due to brackish water encroachment from the saltworks, and direct infiltration of the salts from spray blown by the wind from saltworks; the salts deposited on the soil are transported into the aquifer by infiltrating rainfall and irrigation water tapped in excessive quantity from the confined aquifer (Figure 2a);
v. the salinity of the phreatic aquifer is higher than the confined one.

An artificial recharge experiment has been carried out on the surface phreatic aquifer by means of a drainage trench, and on the underlying confined aquifer by wells; the field test is located in front of the wastewater treatment plant of the Consortium for Cagliari Industrial Development Area (CASIC) (Gallo *et al.*, 1996).

a) b)

Figure 1. Water level contour lines [m] of phreatic (a) and confined (b) aquifers.

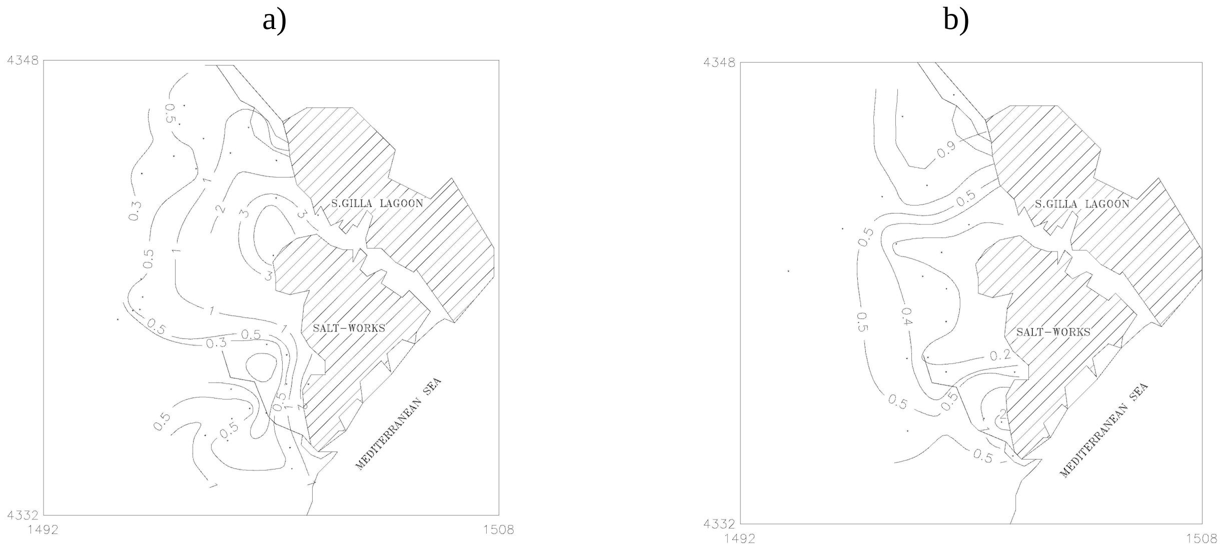


Figure 2. TDS contour lines [g/l] of phreatic (a) and confined (b) aquifers.

DESCRIPTION OF THE MODELLING PROCEDURE

The hydrogeological, conceptual, and mathematical models have been defined to simulate the seawater intrusion phenomena and artificial recharge effects in the aquifer system of Capoterra.

According to the hydrogeological and conceptual models (Sciabica *et al.*, 1993; Sciabica *et al.*, 1996), the mathematical model can be formulated as a coupled system of two partial differential equations, one describing mass conservation for the water-salt solution (the flow equation), and the other one mass conservation for the salt contaminant (the transport equation); flow and transport equations are coupled by means of the constitutive equation relating density of the freshwater-saltwater mixture to the salt concentration.

The numerical solution code of these non linear equations involves spatial discretization with the finite element method following Galerkin's approach, and time discretization using finite differences (Paniconi and Putti, 1995); the results are expressed in terms of equivalent freshwater heads and normalized concentrations at selected time intervals and at each node of the three-dimensional mesh. Validation of the simulation results is performed by comparing these values with hydrogeological and hydrogeochemical data obtained from the monitoring network.

The calibration-validation approach of the code has permitted to discretize horizontally the domain into a two-dimensional mesh with triangular elements and with 165 nodes, as the first simulation phase (Sciabica *et al.*, 1993), 1033 nodes, as the second one (Sciabica *et al.*, 1996), and 2496 nodes, currently. Some wells of the monitoring network have been selected as nodes of the 2D mesh; from these nodes and the vertical layers subdivision of the domain thickness, a three-dimensional mesh with tetrahedral elements is automatically generated by the code.

According to the geology of the plain three homogeneous zones have been defined, the first composed of recent alluvia, the second of ancient terraced alluvia, and the third of fractured granites. Based on the hydrogeological parameters of the aquifers determined by pumping tests in some wells of the control and monitoring network present in the plain, hydraulic conductivity was found to range from k= $2.11 \cdot 10^{-4}$, for the phreatic aquifer, to k=$6.79 \cdot 10^{-7}$, for the confined one. By contrast, to set the longitudinal and transversal dispersivity values, it has been necessary to make an acceptable compromise between stability requirements of the code and soil properties reported in the literature; it was obtained by assuming α_L=100÷1000 m and α_T=10÷100 m. Moreover, the Dirichlet boundary conditions for flow and transport have been defined on the basis of measured piezometric and salinity contour lines.

Pumping simulation. Starting from uniform conditions and imposing boundary ones, simulations have been carried out until steady state conditions were reached; heads and concentrations obtained at each node of the 3D mesh have been used as initial conditions for simulating the pumping effects. Pumping information on dug shallow and drilled wells has been introduced as Dirichlet conditions at the first and fifth layer nodes of the 3D mesh respectively, so that the assumption of no pumping wells in the conceptual model has been removed. Then another steady state simulation has been carried out instead of transient one, due to the fact that as the wells have been exploited for a long time a dynamic equilibrium situation could actually be measured.

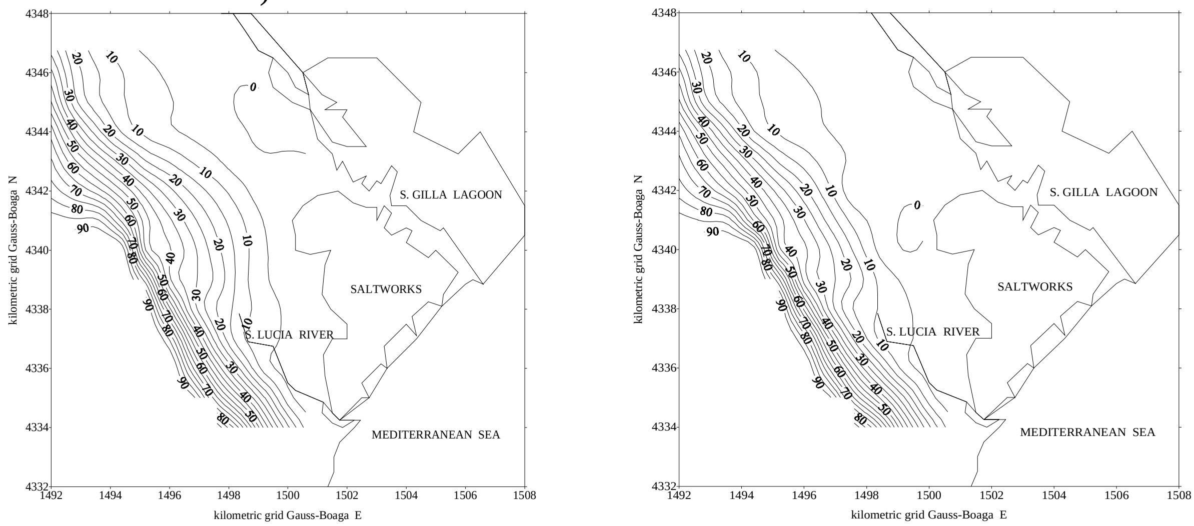
Artificial recharge simulation. According to the different methods applied to carry out the artificial recharge experiment in the phreatic aquifer and in the confined one, two different conditions have been imposed in the simulation, and two new assumptions have been defined in the conceptual model: for the phreatic aquifer, recharged through a drainage trench, the levels mesured in the piezometers have been introduced as Dirichlet condition at nodes of the mesh closest thereto, while for the confined aquifer, recharged through drilled wells, the flux rate for the time test has been introduced as Neumann condition at nodes of the mesh closest thereto.

Results and discussion. In the pumping simulation the water level contour lines constructed by means of the field data from the control and monitoring network (Figure 1) have been reproduced fairly well by the simulation except at the domain boundary. Figure 3 shows the calculated equipotential lines of the aquifers: note the lateral recharge from the western boundary of the domain, the preferential flow direction towards the lagoon, the saltworks and the sea, and the zero contour line coinciding with the drawdown cones of some wells near the lagoon and the saltworks.

According to the boundary conditions relative to the artificial recharge experiments carried out in the aquifer system, the recharge simulation has shown a significant shift of the equipotential lines toward the experiment area only for the confined aquifer; Figure 4 shows the match of the two sets of calculated curves near the recharge area.

With regard to the transport simulation in both pumping and recharge conditions, the calculated equiconcentration lines did not agree well with the measured salinity contour lines due to lack of adequate information, such as detailed knowledge of geological formations and of hydrogeological parameters, and of dispersivity coefficients measurements in both aquifers (as previously mentioned longitudinal and trasversal dispersivity have been obtained from the model calibration based on literature values).

a)



b)

Figure 3. Equipotential lines [m] of the pumping simulation: phreatic (a) and confined (b) aquifers.

a) b)

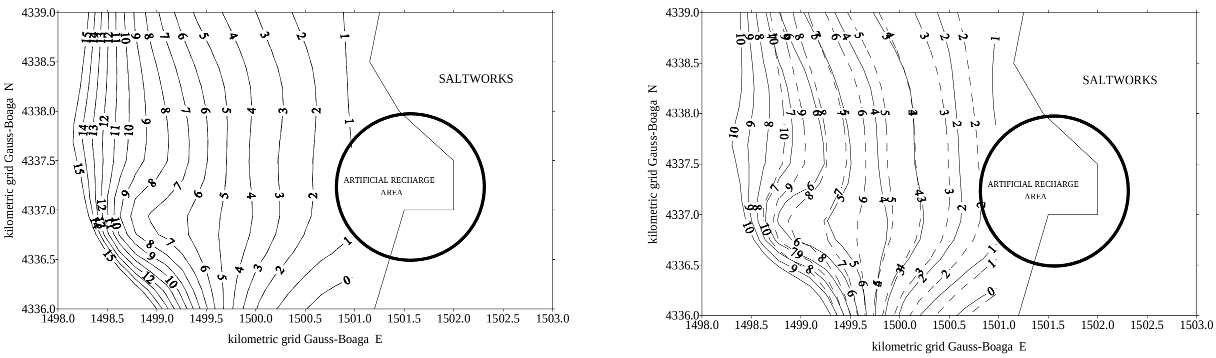


Figure 4. Zoom of the area near the artificial recharge field. Matching of equipotential lines in pumping (continuous line) and artificial recharge (dashed line) simulations: phreatic (a) and confined (b) aquifers.

FIELD ACTIVITIES

Pumping tests. Recently a series of pumping well tests has been performed in the recharge field, aimed at determining the correct transmissivity and storativity values for both the phreatic and confined aquifer. Results are in good agreement with characteristic values of the geological structures in which wells are drilled. Drawdown curves have been analyzed by means of both Jacob and Theis methods, whose results are practically identical.

Tests on the confined aquifer have been carried out for unsteady state flow (lasting three hours) for several constant pumping rates; the corresponding drawdown has been measured in both the well and the two piezometers nearby (about 25 m apart); for the pumping rate of 4.8 m^3/s recovery has been measured until the undisturbed piezometric level was reached; results for that rate show that the laminar flow limit has probably been passed (Table 1). Tests for the phreatic aquifer have also been carried out for unsteady flow for a single pumping rate; drawdown and recovery have been measured in both the well and the piezometer nearby (about 61 m apart) (Table 2).

Comparison of the results of earlier and the latest pumping tests carried out in wells located in different geological areas, a strong heterogeneity for transmissivity (two orders of magnitude) associated with different geological structures can be noted.

Table 1. Transmissivity and storativity for the confined aquifer.

	pumping rate [l/s]	Transmissivity $\times 10^{-4}$ [m^2/s]		Storativity $\times 10^{-4}$ [/]	
		Jacob	Theis	Jacob	Theis
well P9	2.1	8.73	9.39	-	-
	3.1	9.39	8.75	-	-
	4.8	28.33	30.34	-	-
	0.0	12.37	11.53	-	-
well PR1	2.1	8.63	7.46	2.40	2.91
	3.1	8.68	8.75	2.40	2.98
	4.8	23.42	21.48	6.64	2.41
	0.0	9.87	10.76	1.92	2.36
well PR2	3.1	9.00	7.80	3.40	4.70
	4.8	24.40	21.47	7.90	10.36
	0.0	10.10	13.55	2.22	1.30

Table 2. Transmissivity and storativity for the phreatic aquifer.

	pumping rate [l/s]	Transmissivity $\times 10^{-2}$ [m^2/s]		Storativity $\times 10^{-4}$ [/]	
		Jacob	Theis	Jacob	Theis
well S11	4.7	1.70	0.93	-	-
	0.0	1.90	1.32	-	-
well S10	4.7	2.20	2.35	12.00	12.00
	0.0	1.99	2.10	11.50	13.43

Future developments. Owing to the strong heterogeneity in the transmissivity field, a broad field investigation in the whole plain is in progress aimed at determining the order of magnitude of this parameter associated with the main geological areas. Once this has been done, a suitable data inversion technique will be applied to the overall domain, for the purpose of refining the transmissivity field to match equipotential and equiconcentration lines measured in the field.

CONCLUSIONS

While the hydrogeological model has been satisfactorily defined, the conceptual model and solution of the mathematical model need to be better calibrated, especially as far as the transport equation is concerned, using the field data currently being collected. Introduction of new pumping test data into the model will require the geometry of the domain to be better defined. A hydrogeochemical investigation is now under way in an attempt to gain further insight into the saltwater intrusion phenomena occurring in the alluvial plain of Capoterra. The simulation performed has demonstrated that the modelling procedures, from the hydrogeological model to the numerical solution of the mathematical model, can be considered a good operating tool for groundwater resources management, provided that the procedures are founded on accurate information consisting of the hydrogeological and hydrogeochemical data relative to the study domain adequately distributed in space and in time.

REFERENCES

Barrocu, G., Fidelibus, M.D., Sciabica, M.G., Uras, G. (1993). Hydrogeological and hydrogeochemical study of saltwater intrusion in the Capoterra coastal aquifer system (Sardinia). *Proc. 13th Salt-Water Intrusion Meeting*, Cagliari, Italy, 103-111.

Gallo, C., Sciabica, M.G., Uras, G., Vernier, E. (1996). Applicazione di un modello matematico tridimensionale agli elementi finiti ad un esperimento di ricarica artificiale per lo studio dell'intrusione salina nel sistema acquifero della piana di Capoterra. *V Convegno Nazionale dei Giovani Ricercatori di Geologia Applicata*, Cagliari, Italy (submitted).

Sciabica, M.G., Paniconi, C., Barrocu, G. (1993). Three-dimensional model of saltwater intrusion in the Capoterra coastal aquifer system (Sardinia). *Proc. 13th Salt-Water Intrusion Meeting*, Cagliari, Italy, 77-86.

Paniconi, C., and Putti, M., (1995). Picard and Newton linearization for the coupled model of saltwater intrusion in aquifers. *Adv. Water Resour*, (to appear).

Sciabica, M.G (1996), Modeling saltwater intrusion in the Capoterra aquifer system (Sardinia, Italy), *ModelCare 96, Poster Proc., International Groundwater Modeling Center*, Colorado School of Mines, Golden, Colorado, USA, 341-350.